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SUMMARY

The sliding friction and wear of the SiC-nickel based alloy IN-718 couple under line contact test conditions in atmospheric air at a linear velocity of 0.18 m/sec and a load of 6.8 kg (67 N) was investigated at temperatures of 25 to 800 °C. It was found that the coefficient of friction was 0.6 up to 350 °C then decreased to 0.3 at 500 and 800 °C. It is suggested that the sharp decrease in the friction in the range of 350 to 550 °C is due to the lubrication value of oxidation products. The wear rate reaches a minimum of 1×10^{-10} to 2×10^{-10} $cm^3/cm/kg$ at 400 to 600 °C.

INTRODUCTION

Silicon carbide and other ceramic materials are currently receiving much attention for use in high temperature areas of heat engines and other energy conversion systems (ref. 1). In some of these applications sliding or rubbing contact with themselves or other materials can be expected.

The purpose of the present investigation was to measure the friction and wear of sintered alpha SiC in sliding contact with the nickel-based alloy IN-718 at 25 to 800 °C in atmospheric air at a load of 6.8 kg (67 N) and a linear sliding velocity of 0.18 m/sec. A double rub block test machine with line contact of the static SiC blocks pressed against the circumferential surface of a rotating IN-718 disk was used. Friction and wear are reported and the sliding surfaces were examined by Scanning Electron Microscope (SEM) and Energy Dispersive X-rays (EDX).

BACKGROUND INFORMATION

Sliding wear and friction of polycrystalline and single-crystal SiC against itself and other ceramic and metallic materials under a wide variety of conditions has been reported (refs. 2 to 9). A brief review of a few selected articles under several conditions follows. The wear rate and friction of sintered polycrystalline alpha SiC sliding against itself in air at room temperature at a sliding velocity of 0.5 to 1.4 m/sec and a load of 22.7 kg (225 N) in a ring test is 10^{-6} to 10^{-7} $cm^3/cm/kg$ and the coefficient of friction is 0.41 to 0.44 (ref. 2). Even though run at room temperature frictional heating raised the general contact area to 350 °C in 5 to 6 min of sliding. (Other studies have measured asperity contact temperatures for dry sliding (Si_3N_4 on sapphire) as high as 2700 °C (ref. 3).) The surface oxygen content increased from 0.1 wt % initially to 0.6 to 10.6 wt % after test, the higher oxygen was at the higher sliding velocities. This indicates oxidation of the SiC to form SiO_2 coated grains. Thus, after a short time, sliding was SiO_2 against SiO_2. Evidence of plastic deformation, cracking, and ploughing were observed.

Sliding of single-crystal SiC against polycrystalline metals in vacuum at room temperature reveals that the coefficient of friction is related to the relative chemical activity of the metal (ref. 5). In vacuum the more active the metal the higher the coefficient of friction. In vacuum Al,Ti,Cu,Ni,Co,Fe, Rh, and W all transfer to the SiC surface in sliding contact. Ti and Al which have stronger chemical affinity for SiC (smaller d-character of the metal bond) (ref. 6) and lower theoretical shear strength (ref. 6) exhibited the greatest amount of transfer to the SiC in vacuum. SiC wear debris, produced by brittle fracture, causes grooves and indentations in the surface of both the metal the SiC (ref. 5).

Surface contaminates play a large role in the sliding of SiC against metals because they alter the chemical and mechanical behavior of the surface (ref. 6). For a sputter cleaned iron surface sliding against single-crystal SiC in high vacuum at temperatures to 250 °C the coefficient of friction remained low due to the presence of absorbates such as oxygen and carbon originally on the surface of the SiC. Then the coefficient increased rapidly with increasing temperature in the range of 400 to 800 °C while the absorbed carbon contaminant decreased rapidly. This large increase in the coefficient above 400 °C is due to the loss of surface absorbed contaminates. Above 800 °C the coefficient decreased rapidly with rising temperature. This was correlated with the graphitization of the SiC surface.

Friction and wear of polycrystalline SiC sliding against polycrystalline metal alloys in air at room temperature to 800 °C in a variety of test contact geometries has produced a diversity of results which in essence say that the results are dependent on the alloy and test conditions (refs. 7 to 9). In general the coefficient of friction decreases with an increase in temperature due to the formation of more or less lubricating metal oxides in the sliding contact. This is often called "glazing." These oxides are the result of the oxidation of the SiC and metal. The presence of this oxide scale does not always lead to less wear of the couple.

Several oxides have been tested for lubricity in metal sliding couples (ref. 9). The following list is arranged in the order of increasing lubricity:

$$NiO, Fe_3O_4, Cr_2O_3, WO_3, Cu_2O, ZnO, Co_2O_3, MoO_3, PbO$$

It was observed that as the lubricity of these oxides increased their hardness decreased.

A few comments on the oxidation and reaction of SiC and IN-718 are in order because of the known and possible influence of reaction and oxidation products on the tribological properties of sliding contacts in air. In passive, isothermal, nonsliding oxidation of SiC without excess (free) Si an adherent, protective SiO_2 film is formed on the grains. Growth rates of these films follow parabolic kinetics which implies diffusion control. This process proceeds by inward diffusion of oxygen through the SiO_2 film where it reacts with the SiC to produce more SiO_2 and CO gas. The gaseous CO diffuses outward and is the rate controlling step (ref. 10). A region of silicon oxycarbide is formed between the surface SiO_2 scale and the carbide. It can be speculated that the rubbing contact of a sliding couple will rupture the protective SiO_2 film or even scrape it off and this may lead to accelerated oxidation.

Many SiC products contain free silicon to the extent of 14 to 24 vol % (ref. 11). The morphology is typically angular SiC grains dispersed in a matrix of silicon. Oxidation of silicon is similar to that of SiC (ref. 10). It can be surmised that the oxidized surface of the composite will be more heavily coated with SiO_2 and this may lead to a tribologically different surface.

Crystalline SiO_2 exists as several polymorphic forms and each has several crystalline modifications. Large and often rapid volume changes are associated with these crystalline transformations from one modification to another. For example, alpha quartz rapidly transforms to beta quartz at 573 °C with a volume expansion of 1.6 percent. It has been reported (ref. 12) that at and above the alpha to beta quartz transformation temperature a sudden and large increase occurs in the friction of a sliding metal couple coated with fine alpha quartz powder.

Oxidation of Ni in isothermal and passive, nonsliding conditions also proceeds by parabolic kinetics which also implies diffusion control of the growth rate of the NiO scale (ref. 13). For the alloy IN-718 which contains other elements as Fe,Cr,Nb,Ti and etc. the rate and the nature of the oxide scale is modified. Spinels and other oxides as well as NiO are formed. In general the addition of small amounts of alloying elements (<10 wt %) to Ni increases the oxidation rate. At greater amounts (>10 wt %, especially Cr), the oxidation resistance can be improved. However, in the case of a sliding contact it can be suggested that the rate of oxidation of the alloy may be changed due to the sliding forces. On one hand this sliding may increase the rate due to removal of the protective scale from the metal. On the other hand, glazing (vitrification) of the surface oxide may be produced by the sliding. This vitrified glaze may actually have a lower wear rate and afford superior oxidation protection compared to the undisturbed crystalline oxide scale. Also, the surface composition may be altered by the sliding action such as NiO may be the primary scale in sliding and Cr_2O_3 or other oxides in static conditions.

Studies of SiC and alloy (IN-718) reactions have been made using static reaction couples in limited oxygen atmospheres (refs. 14 and 15). The results indicate extensive reaction as low as 700 °C between SiC containing free Si, but only limited reaction even at 1000 °C with SiC containing no free Si.

EXPERIMENTAL

A double rub block wear and friction apparatus was used for all tests. Figure 1 is a photograph which shows the geometry of the critical parts. Two rub blocks are pressed against the rotating disk by pressurizing the bellows and the frictional torque is transmitted via the torque arm to a measuring and support system. A line contact with the blocks and the disk is produced and this line is maintained by the pivoting block holders. The disk is 3.492 cm diameter and 1.28 cm thick and the rub blocks are 2.22 cm long by 0.63 cm wide and 1.11 cm deep. The torque system is calibrated with dead weights.

Induction heating is used to bring the disk to the test temperature. The temperature of the disk surface is measured by an optical pyrometer.

All determinations are made in atmospheric air at ambient pressure with a relative humidity of 45 to 55 percent. Each rub block is loaded to 6.8 kg (67 N) and the sliding velocity is 0.18 m/sec.

A determination involved the following: The sliding surface of the IN-718 disk is polished first with a dry felt cloth and levigated alumina then rinsed with distilled water. Next it is polished again with a water wet cloth and levigated alumina then rinsed with distilled water and rubbed with a clean felt cloth and finally rinsed with water followed by ethanol and dried. The rub blocks are used as received with only an ethanol rinse to remove surface oils. The arithemic mean surface roughness (Ra) of both blocks and the disk were measured. After assembly of the test apparatus the linear sliding velocity is set but the rub blocks are not loaded. The induction generator is turned on and the disk surface is heated over a 15 min period to the test temperature. Both blocks are now pressed against the revolving disk by pressurizing the bellows and the friction force is recorded over a period of 60 min. After the test the blocks and disk are allowed to cool to room temperature, then removed and the wear debris collected and stored.

After test several measurements are made on the blocks and disk for the purpose of determining the roughness and the wear volumes. The surface roughness (Ra) in the wear track of the disk and wear scar of the blocks is measured. This measurement is made at a right angle to the wear direction, that is, across the track or scar. A profilometer trace at four locations on the wear track of the disk is made. In a similar way three traces are made of the wear scar on the SiC blocks, one made at each end and the center of the scare. From the latter measurements the wear volume of the blocks and disk are determined. From the profilometer traces squares are counted to obtain the area and then multiplied by the length to obtain the wear volume.

Wear factors were calculated from profilometer determined wear volumes by:

$$\text{Wear volume } (cm^3)/\text{sliding distance } (cm)/\text{load } (kg)$$

this value is the average wear rate, K, over the test duration. Since the sliding distance, velocity and load are maintained constant these wear rates will be used for comparative purposes.

A listing of the nominal compositions of IN-718 alloy and the sintered α SiC are presented in table I. The SiC bulk density is calculated from the measured weight and volumes of the machined blocks. SiC is 97.5 percent of theoretical density indicating some porosity. This porosity is clearly evident in the photomicrograph of the polished cross-section in figure 2(a). A dual magnification SEM photograph of the as machined surface of a SiC rub block is given in figure 2(b), this is the morphology of the sliding test surface. The largest pores in this surface are about 5 μm in diameter. The grains have the appearance of elongated cylinders with a flattened surface caused by machining. The elongated or cylindrical grain structure (aspect ratio 3.2) and a nominal grain size of 4 μm is reported as typical for sintered α-SiC (ref. 11). The surface roughness (Ra) of the SiC rub block test surface is 0.3 μm (12 μin.) and the IN-718 is 0.2 μm (8 μin.). The Knoop microhardness of the IN-718 at an indentor load of 100 g (1 N) is 517 ± 4 kg/mm^2 at room temperature (ref. 11) and 1800 kg/mm^2 at 800 °C (ref. 16). The Knoop hardness of the polished SiC surface shown in figure 2(a) at an indentor load of 200 g (2 N) is 2418 kg/mm^2 at room temperature.

RESULTS AND DISCUSSION

Friction

Figure 3 is a plot of the coefficient of friction in relation to sliding distance for several couples at temperatures of 25 to 800 °C. The coefficient of friction of the SiC-IN 718 couple starts out at about 0.4 at both 25 and 350 °C then increases to almost 0.6 at 300 m then remains constant. However at 550 and 800 °C it starts near 0.3 and remains there. Visual examination of the disk at 350 °C indicates no oxidation tarnish layer while at 550 and 800 °C a brownish colored tarnish layer is present. This suggests that the tarnish or oxide layer present at 550 and 800 °C is the cause for the decreased friction at these temperatures.

Additional information about alloy element transfer was obtained by closer examination of the disk wear tracks and the SiC wear scars by SEM and EDX methods. Figures 4 and 5 include SEM photographs and EDX for Si and Ni along the scan line across the disk wear tracks at 350 and 550 °C, respectively. All the alloy elements show the same relative linear distribution so only the Ni element is shown. Both figures indicate transfer of Si from the SiC at numerous streaked areas.

Figures 6 and 7 are SEM photographs and EDX line scans across the wear scars on the SiC and both show disk element transfer. A study of the SEM's as well as the element distributions gives the impression that the alloy elements are more abundant in the wear scar at 550 °C than at 350 °C. This is especially true if one assumes that the small island in the figure 8(a) SEM is a remnant of the surface transfer alloy elements that originally more extensively covered the scar before spalling off on cooling. The general lack of Si is taken as an indication of more extensive alloy element transfer. Silicon from the underlaying SiC is absent due to cover up by the transferred alloy elements to such a depth that the electrons of the beam does not penetrate. Comparison of the SEM images in figures 8(a), 9(a), and 10(a) shows the increase in alloy transfer with rising temperature. Bright areas in the back scatter electron images are alloy transfer regions. From 25 to 350 °C a small increase is apparent but a larger increase is evident from 350 to 500 °C. This impression of more extensive alloy element transfer is reinforced by the results in figure 11 at the edge of the SiC wear scar at 550 °C. There is a high concentration of Ni and Cr in the wear scar. From this information it can be concluded that greater alloy transfer occurs at 550 °C than at 350 °C and this may lead to the lower friction observed at 550 °C.

The above information, with the exception of the observed tarnish layer, gives no indication of whether or not the transferred elements are oxidized. XRD results of the wear debris and oxygen distribution determined by EDX indicate that oxidation has occurred. At both 350 and 550 °C SiC, NiO and other unidentified phases were detected in the wear debris by XRD. The SiC lines are narrow and sharp, however, the NiO lines are broad and diffuse. The wear debris is a very fine powder. The broad and diffuse nature of the NiO lines suggests that it is very fine. The other unidentified phases may be SiO_2,

Cr_2O_3, and spinels. It is interesting to note that XRD results of an isothermally oxidized surface of IN-718 in nonsliding conditions at 800 °C reveals only Cr_2O_3 as the oxidation product. This indicates that the sliding action alters the oxidation products of IN-718 or at least the degree of crystallinity, particle size, and relative mixture.

Nickel, silicon, oxygen, and carbon distributions determined by digital EDX line scans in the SiC wear scars at 350 and 550 °C are presented in figures 12 and 13. There is, in general, a good correlation between Ni and oxygen, when the Ni is high, oxygen is also high. Only the Ni distribution is given because the other alloy elements follow in the same way. This indicates that the transferred alloy elements are present as oxides due to oxidation. A similar correlation between Si and carbon is also present but it is less satisfactory due to the much greater difficulty in carbon measurement by the EDX method. Also, there appears to be no correlation between the Si and oxygen distribution indicating little oxidation of the SiC. This is a very tentative conclusion because the EDX method may not be capable of detecting the oxygen in the thin SiO_2 films formed on the SiC grains.

This evidence allows the conclusion that the transferred alloy elements are oxidized which in turn allows the tentative conclusion that the lower friction at 550 °C and above is due to the presence of a lubricative metal oxide film in the sliding contact area.

Included in figure 3 are results for the sliding couples IN-718-IN-718 and fused silica-IN-718 at 25 and 800 °C. This friction information was obtained at a higher linear sliding velocity but it may be used for comparative purposes. Its incorporation is included, because the oxidation of SiC leads to the formation of SiO_2 and IN-718 sliding on itself is a base line condition.

At 25 °C the friction of the IN-718-IN-718 couple is about constant at or near 0.5, while the friction of the fused silica-IN-718 starts out at 0.4 and then drops to 0.3 by 300 m and then remains constant. This is the lowest of all three rub block materials. Visual observation through the transparent silica rub blocks during sliding revealed many bright red, high temperature, flickering spots at the sliding contact due to frictional heating. Since fused silica has poor thermal conductivity compared to the alloy or SiC the metal-silica interface may reach a higher temperature which will produce more oxide formation and thereby lower friction. However, the wear factors of the three rub blocks are significantly different (for the SiC rub block it is 3.1×10^{-10}, for IN-718 block it is 5.5×10^{-9} and the fused silica 2×10^{-8} $cm^3/cm/kg$). The large wear factor for the fused silica shows that even though its friction is the lowest of the three rub block-IN-718 couples does not necessarily mean that the wear will also be the lowest.

At 800 °C, except for the IN-718 up to 60 m, the coefficient of friction for all three couples is approximately the same. This may be explained by the formation of a lubricating scale of the same or similar composition thus the friction is independent of the rub block composition. Also the wear factors are similar (8.1×10^{-10} for the SiC rub block, 1.3×10^{-10} for the fused silica and 5.4×10^{-10} for the IN-718).

Sliding friction is an important parameter in tribology, but the smoothness of sliding is also significant. If sliding were completely smooth and continuous the recording of the frictional torque versus distance of sliding would be a narrow line on the recorder chart. However, this is not the case, in fact the recording has a considerable and variable width. The width of this band is caused by a stick-slip phenomenon. In this process the rub block, after normal sliding for a short distance, becomes adherent or welded to the rotating disk, this produces added torque above that caused by the steady-state friction. As this torque builds the recorded friction increases. Stress builds in the weld and fracture eventually occurs, releasing the added torque. The amplitude of this superimposed torque factor produces the band width. Stick-slip was visually observed in a high speed movie of a ceramic-metal couple. Stick-slip occurs repeatedly over a short time span. Fracturing of the weld contributes to wear of the couple, and fracturing produces wear debris.

Table II is a listing of band width versus sliding distance for the SiC-IN-718 couple. The smaller the band width the smoother the sliding. The base-line band width is 0.01 and is caused by machine irregularities and electrical noise. After a short run-in distance the band width at 25, 350, and 550 °C decreases, however, at 800 °C the values remain high for the total test distance.

Figure 14 presents sliding friction information for IN750, taken from reference 16, and IN-718 against SiC in air versus temperature. The IN750 data was obtained from a pin on disk test at higher linear sliding velocity but lower load. For both alloys the friction decreases with increasing temperature. There is little change for the IN-718 up to 350 °C then a large decrease at 550 °C. The IN750 with a higher Ti but lower Fe, Nb, and Cr content decreases more or less monotonically up to 900 °C. This information indicates a difference in sliding friction for the two alloys against SiC. This may be due to the difference in amount (kinetics of oxidation) and composition of the oxide scale formed and/or a difference in the test velocities. The IN750 test was conducted at a velocity of 9 m/sec compared to 0.18 m/sec for the IN-718. At the higher velocity a higher contact interface temperature would exist for a given bulk temperature and this could lead to lower friction.

Sliding friction information (ref. 7) for iron against polycrystalline SiC in high vacuum at temperatures to 1200 °C and discussed previously is given in figure 15 along with the present data for the couple IN-718-SiC sliding in air. This shows the large difference that atmosphere may have on a similar couple.

Change in the surface roughness as a consequence of sliding 648 m at 0.18 m/sec and a load of 6.8 kg (67 N) is presented in figure 16 at 25 to 800 °C. These measurements were made at a right angle to the sliding direction or across the wear area. The SiC rub blocks have a smaller increase in roughness than the IN-718 disk but both exhibit an increase with temperature. This result for the SiC can be explained by the increased element transfer, cracks, and plowing of the surface as seen in figures 9, 10, and 11. It is suggested that the increase in roughness of the alloy disk is caused by oxide buildup on the SiC rub blocks which in turn scratches and gouges the alloy surface. Also presented in figure 16 are roughness data for the IN-718 sliding against IN-178 at 0.5 m/sec for a total of 1800 m at 25 and 750 °C. The roughness of the disk changed little while the block roughness increased with temperature.

Wear

Table III is a listing of the wear factors of the SiC rub blocks and the IN-718 disks. Figures 17 and 18 are plots of this data. Figure 17(b) is the data for the SiC rub blocks and figure 18 is the corresponding data for the IN-718. Edge chipping of the SiC rub blocks was observed. This chipping is aggravated by the relatively low fracture toughness of SiC. Figure 19 is a photograph of the wear scars on the SiC rub blocks. The 550 and 800 °C blocks are sputter coated with gold for SEM examination. From this photograph a visual progression of the width of the wear scars with temperature is clearly evident. The minimum scar width is at 550 °C which is also the point of the minimum wear factor. A minimum in the wear of the SiC in the region of 400 to 600 °C of 1×10^{-10} to 2×10^{-10} $cm^3/cm/kg$ is suggested. Wear of this magnitude is considered to be quite small.

Unpublished work of the authors on transparent fused silica detected a minimum wear factor in this same temperature range. This seems to indicate that the SiO_2 formed on the surface of the SiC by oxidation causes it to wear as if it were SiO_2.

The Si and Ni content in the wear scar on the SiC rub blocks and in the wear tracks on the disks at each temperature were determined by use of area EDX analysis to determine relative element transfer. The Ni/Si ratios in the rub block scars at 25, 350, 550, and 800 °C along with the corresponding Si/Ni ratios in the disk wear tracks are presented in figure 17(a). There is a maximum of metal transfer to the SiC rub block and a minimum of Si transfer to the disk at 550 °C. In this temperature range a minimum in the wear rate of the SiC rub blocks occurs. The implication is that the sliding condition which produces the maximum transfer of Ni to the SiC and the minimum transfer of Si to the disk results in the lowest wear of the SiC. It was observed that the metal elements transferred to the SiC rub blocks were always in the same proportion as in the disk which translates to the conclusion that no preferential alloy element transfer occurred.

The wear debris collected from the test chamber at the end of sliding was chemically analyzed for Ni and Si. The Ni/Si and NiO/SiC ratios were calculated and are tabulated in table IV. Calculation of the NiO/SiC ratio was made possible from the XRD information. Both the metal and compound ratios at 25 and 350 °C are equal, however they decrease at 550 and 800 °C. This indicates that the Si in the wear debris is increasing relative to the Ni or the Ni is decreasing relative to the Si at temperatures of 350 °C or above. If all the Ni is from wear of the IN-718 disk and the Si is mainly from the SiC rub block, then the logical conclusion to be drawn is the wear rate of the IN-718 is decreased relative to the the SiC at temperatures above 350 °C.

Dividing the wear rate factors (table III) for the disk by those of the SiC rub block for each temperature gives a disk to SiC wear ratio. These ratios show a trend with temperature similar to the above wear debris results, that is, with rising temperature the wear of the disk decreases relative to that of the SiC.

Both plastic deformation and cracking along with wear debris and pores are visible in the SEM images of the SiC wear scar in figures 9(b) and (c) at 25 °C. At 350 and 550 °C the deformation is evident but no cracking was detected. Plastic deformation and cracking have been identified as the main mechanisms of wear in ceramics (ref. 18) and it is suggested it is probably true for SiC as well.

Another contributing factor to increased wear of ceramic materials is porosity. It is reported (ref. 19) for Al_2O_3 that an increase of 10 percent in porosity doubles the wear. Porosity in ceramics leads to lower strength and since wear is the result of fracture the lowered strength caused by porosity produces increased wear. It is probable that the porosity of the SiC observed in figures 2(a) and (b) contributes to increased wear of the SiC.

CONCLUSIONS

After investigation of the friction and wear of the SiC-IN-718 line contact sliding couple in air the following conclusions have been drawn.

1. The coefficient of friction is 0.6 at 25 and 350 °C then drops to 0.3 at 550 and 800 °C.

2. An increased transfer of alloy elements at 550 °C and higher and oxidation to a lubricative scale is suggested as the cause of the decrease in friction at the higher temperatures.

3. A minimum wear rate of the SiC of 1×10^{-10} to 2×10^{-10} $cm^3/cm/kg$ was reached in the range of 400 to 600 °C. This corresponds to the maximum Ni transfer to the SiC and the minimum transfer of Si to the IN-718 disk.

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TABLE I. - NOMINAL COMPOSITION AND DENSITY OF SINTERED α-SiC AND IN-718 ALLOY

IN-718, wt %		α-SiC, wt %	
Cr	18.6	SiC	98
Mo	3.1	B	0.6
Nb	5	Al	.07
Fe	18.5	Fe	.3
Ti	.9	C	1
Al	.4	Bulk density = 3.13 grs/cm^3	
Si	.3	Theoretical density = 3.21 grs/cm^3	
Mn	.2	Percent of theoretical	
C	.04	density = 97.5	
Ni	53 (by difference)		
Density = 8.19 grs/cm^3			

TABLE II. - FRICTION COEFFICIENT BAND WIDTH FOR SiC SLIDING ON IN-718 AT 0.18 m/sec

[6.8 kg (67 N) load, 45 to 55 percent RH.]

Temperature, °C	Coefficient of Friction Band Width								
	all	22	54	108	216	324	432	540	648
25	0.03	0.02	0.03	0.03	0.02	0.01	0.02	0.01	0.02
350	.04	.06	.03	.05	.01	.01	.02	.01	.01
550	.06	.02	.02	.02	.03	.02	.03	.03	.04
800	.06	.06	.02	.05	.08	.07	.07	.07	.05

[a]Sliding distance (m).

TABLE III. - AVERAGE WEAR FACTORS K ($cm^3/cm/kg$) FOR THE SiC RUB BLOCKS AND IN-718 DISKS

[Linear velocity 0.18 m/sec and 67 N (6.8 kg) load.]

SiC rub block,[a] °C				IN-718 disk, °C			
25	350	550	800	25	350	550	800
3.1×10^{-10}	3.8×10^{-10}	1.2×10^{-10}	8.1×10^{-10}	7.7×10^{-10}	4.1×10^{-10}	5.8×10^{-10}	7.3×10^{-10}

[a]Average of left and right rub blocks.

TABLE IV. - WEAR DEBRIS COMPOSITION RATIOS

Temperature, °C	Ratios	
	Ni/Si	NiO/SiC
25	14	12.7
350	14	12.7
550	11.4	10.1
800	6.2	5.5

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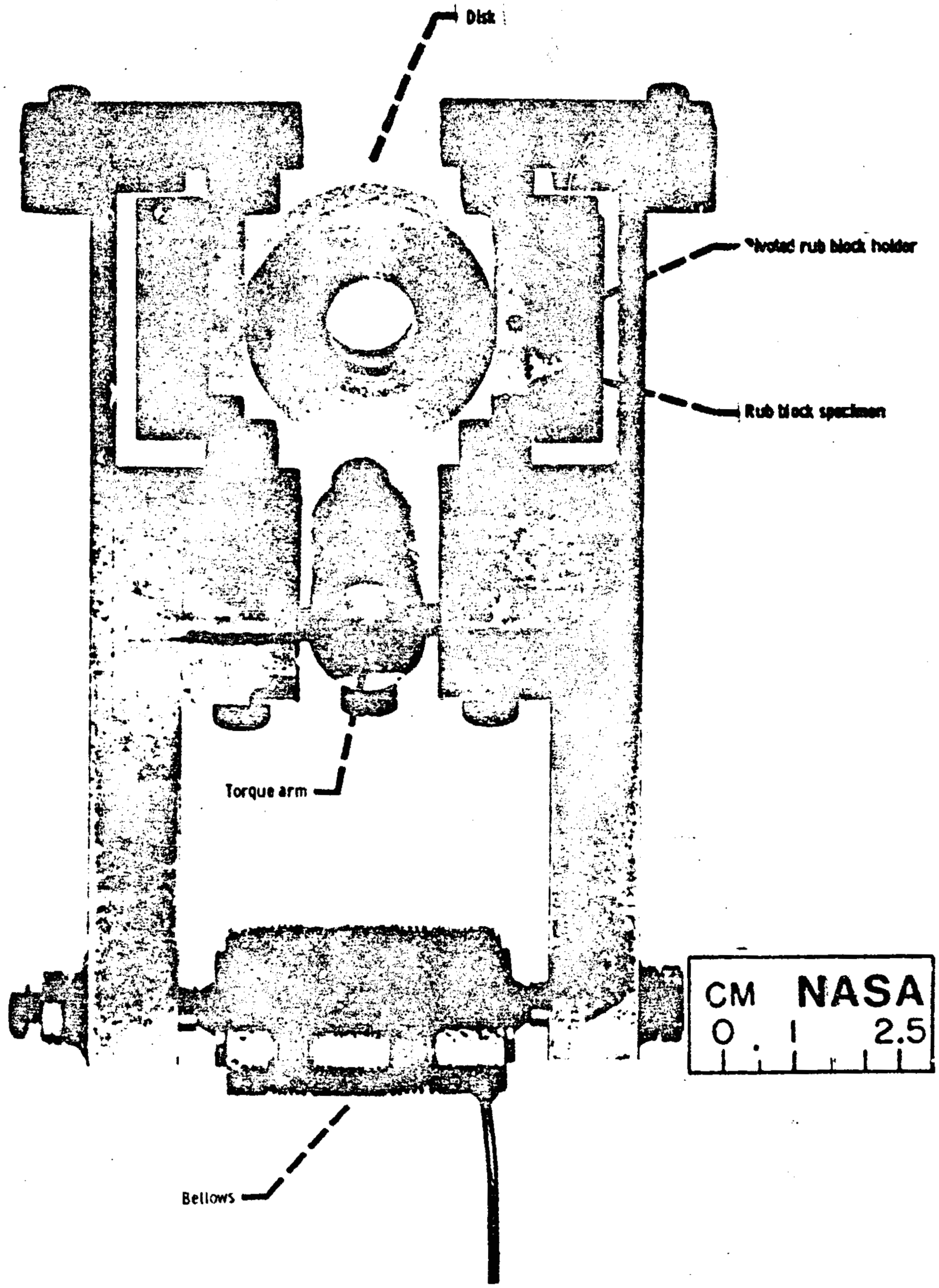

Figure 1. - Double rub block friction and wear tester.

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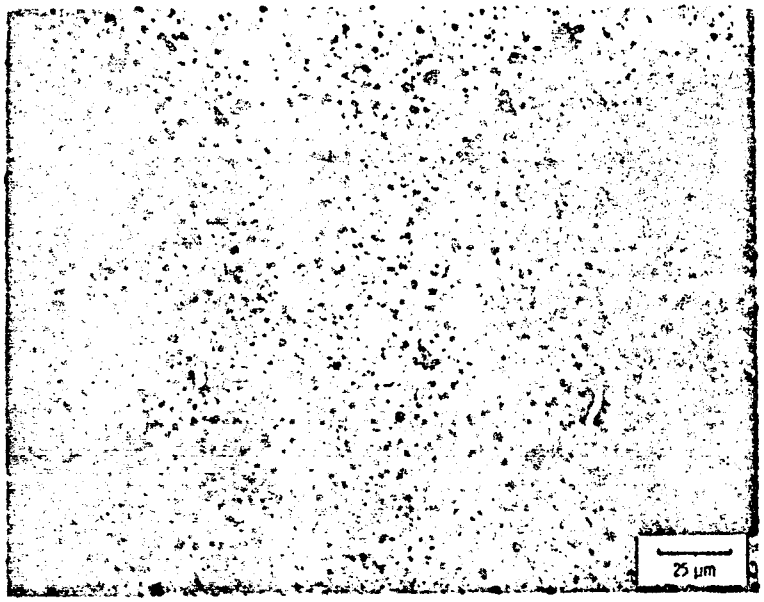
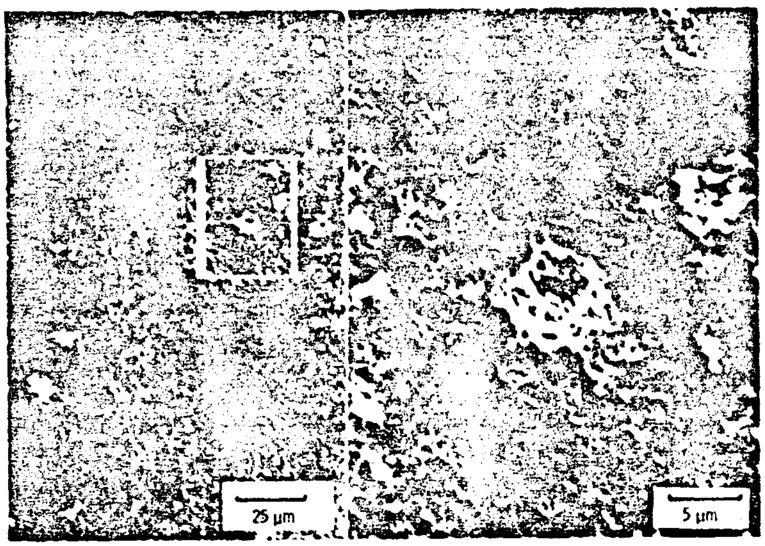


(a) Optical micrograph of the polished-unetched cross-section.



(b) Prepared test surface-secondary election dual SEM image. Au coated.

Figure 2. - Photomicrographs of SiC test specimens.

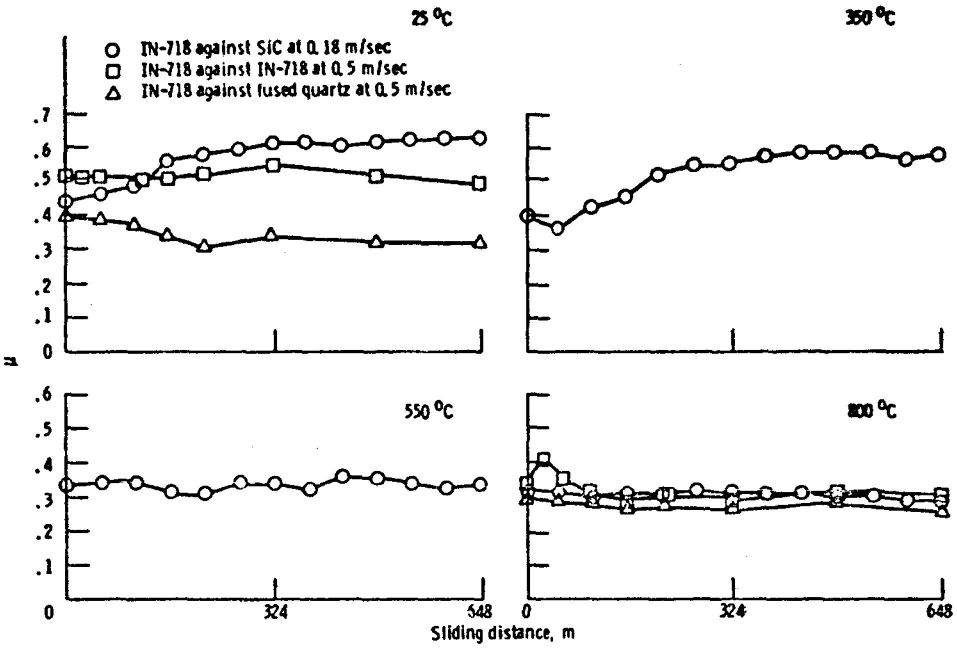


Figure 3. - Coefficient of friction (μ) for SiC, IN-718 and fused silica sliding against IN-718 in air at a load of 6.8 kg (67 N) rub block.

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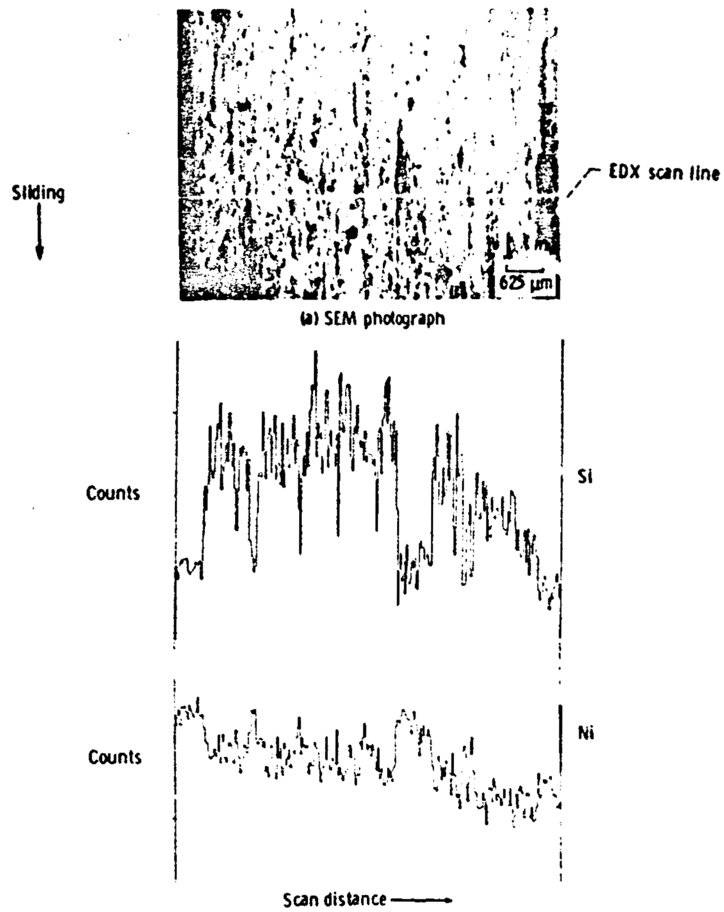

(b) EDX digital line profile for Ni and Si.

Figure 4. - SEM and EDX of IN-718 disk wear track after sliding on SiC at 350 °C.

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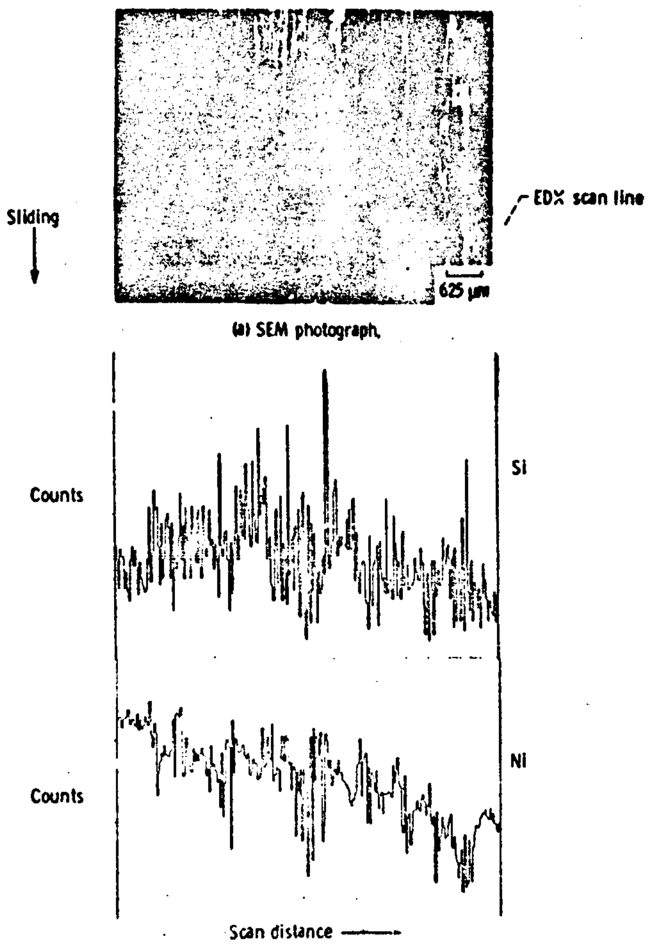

(a) SEM photograph.

(b) EDX Digital line profile for Ni and Si.

Figure 5. - SEM and EDX of IN-718 disk wear track after sliding against Si -• 550 °C.

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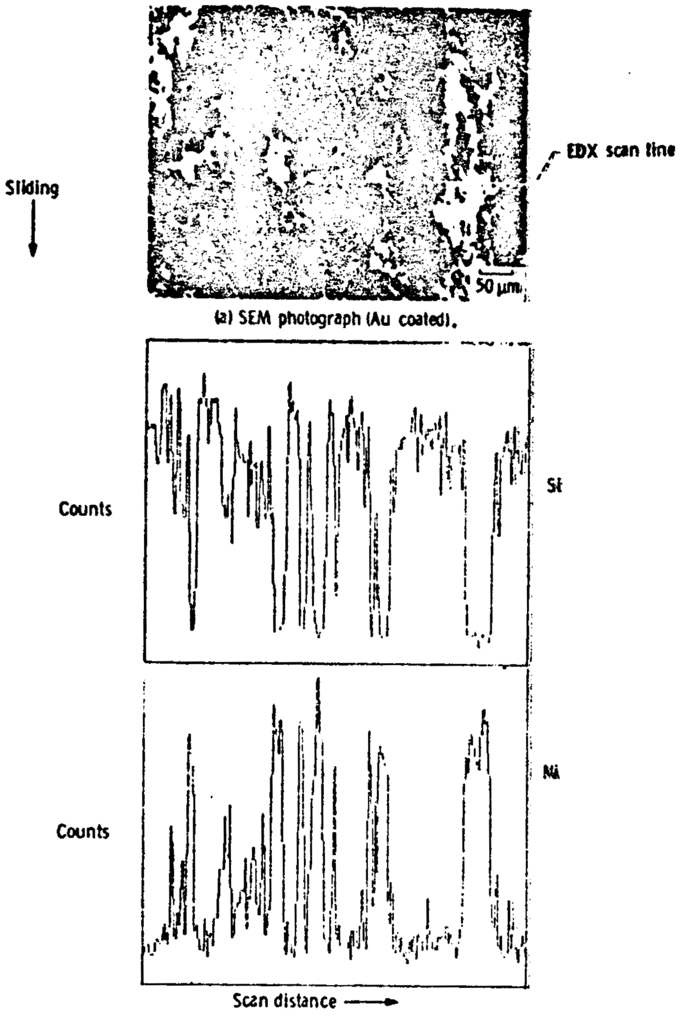

(b) EDX digital line profile for Ni and Si.

Figure 6. - Element distribution in SiC wear scar after sliding against IN-718 in air at 350 °C.

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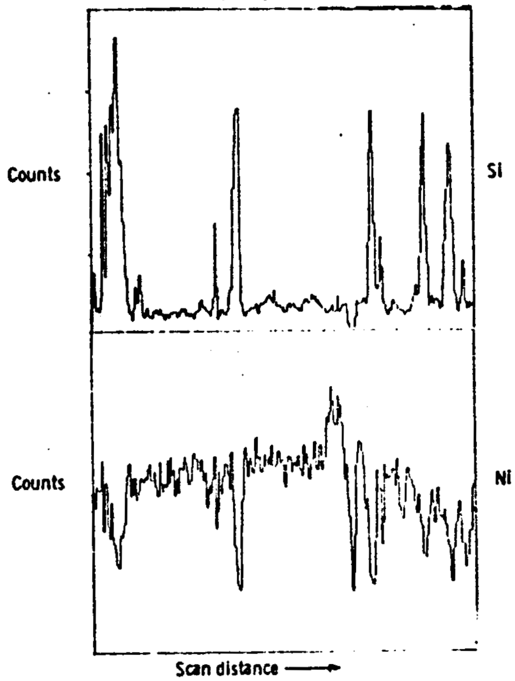
(a) SEM photograph (Au coated).



(b) EDX digital line profile for Ni and Si.

Figure 7. - Element distribution in the SiC wear scar after sliding against IN-718 in air at 550 °C.

(a) Back scatter electron image SEM.

Secondary electron image Back scatter electron image

(b) Back scatter and secondary electron image SEM.

(c) Back scatter electron image SEM.

Figure 8. - SEM images of SiC wear scar after sliding against IN-718 at 25 °C.

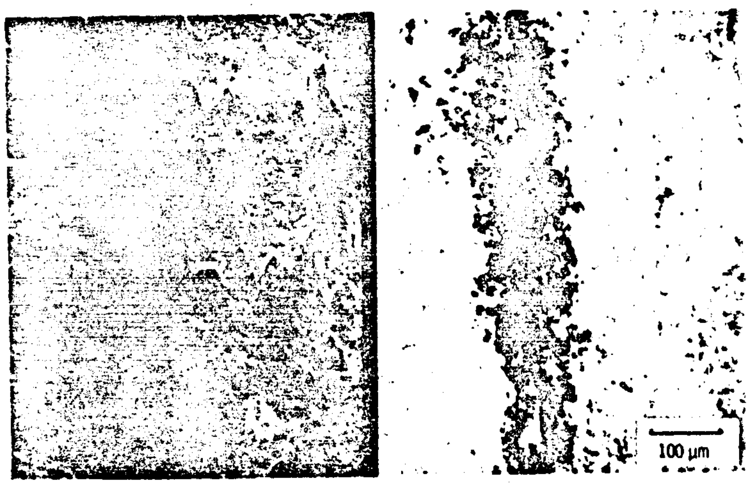
(a) Back scatter electon image SEM.

Secondary electron image Back scatter electron image

(b) Secondary and back scatter images SEM.

Figure 9. - SEM images of the SiC wear scar after sliding against IN-718 at 350 °C.

(a) Back scatter electron image SEM.

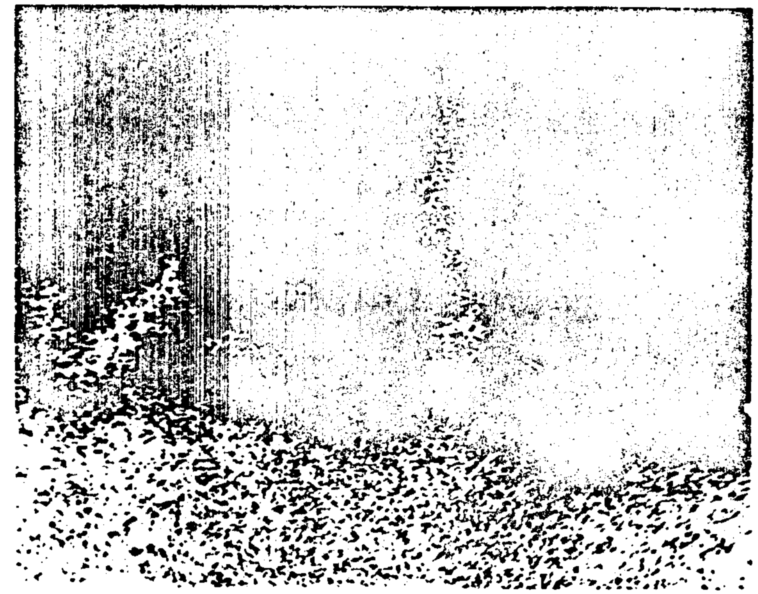


Secondary electron image Back scatter electron image

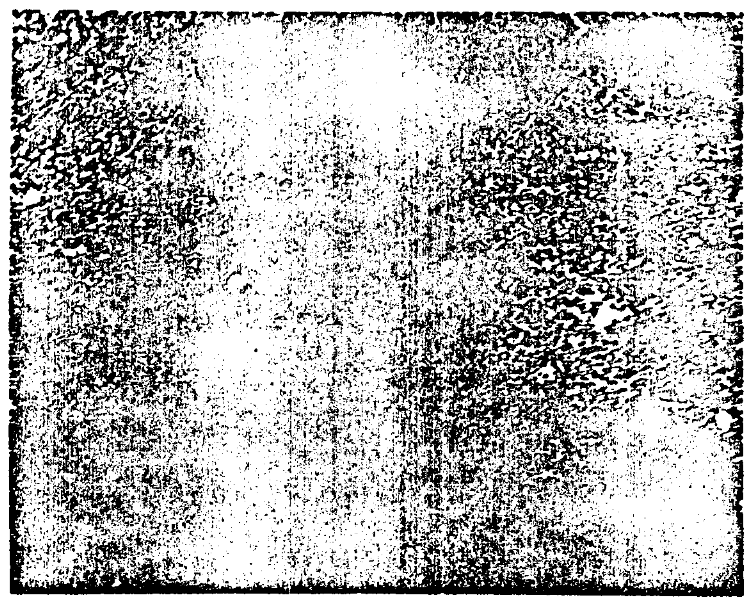
(b) Back scatter and secondary electron image SEM.

Figure 10. - SEM images of the SiC wear scar after sliding against IN-718 at 550 °C.

(a) SEM photograph.



(b) EDX analog dot scan for Si.



(c) EDX analog dot scan for Ni and Cr.

Figure 11. - SEM photograph and analog dot maps at edge of SiC wear scar after sliding against IN-718 at 550 °C.

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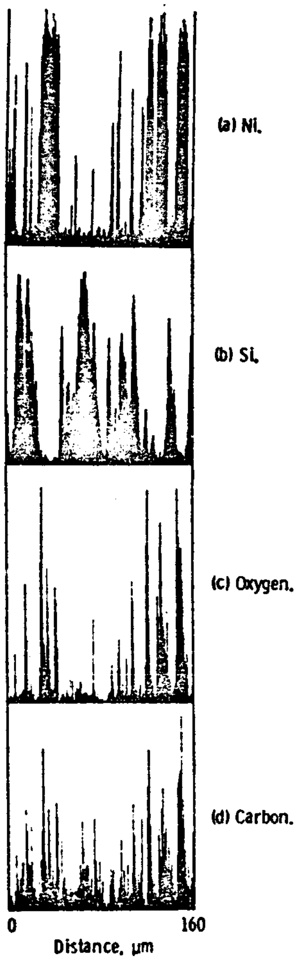


Figure 12. - EDX Line scan in SiC wear scar test temperature of 350 °C.

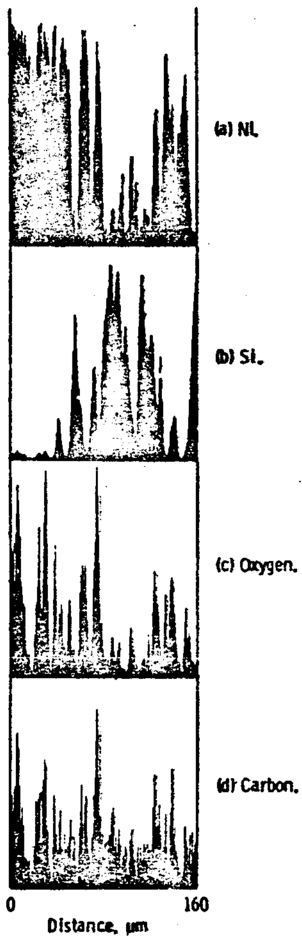


Figure 13. - EDX Line scan in the SiC wear scar test temperature of 550 °C.

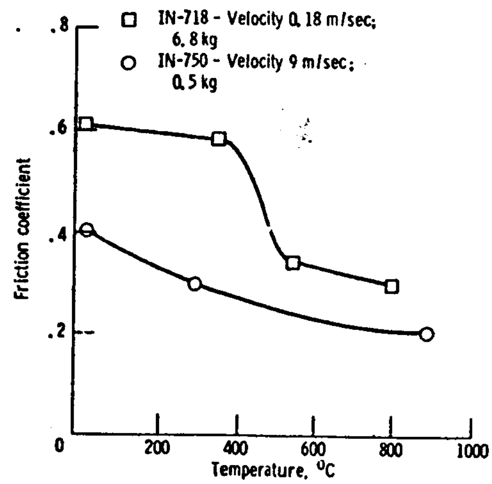


Figure 14. - Friction versus temperature in air at atmospheric pressure for SiC sliding against IN-718 and IN-750 alloys.

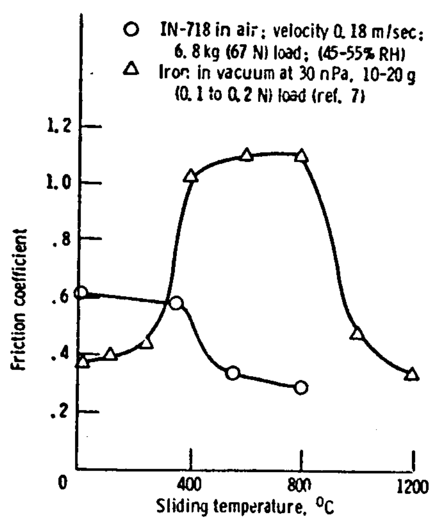


Figure 15. - Effect of temperature on friction for sintered polycrystalline α-SiC on metals in air and vacuum.

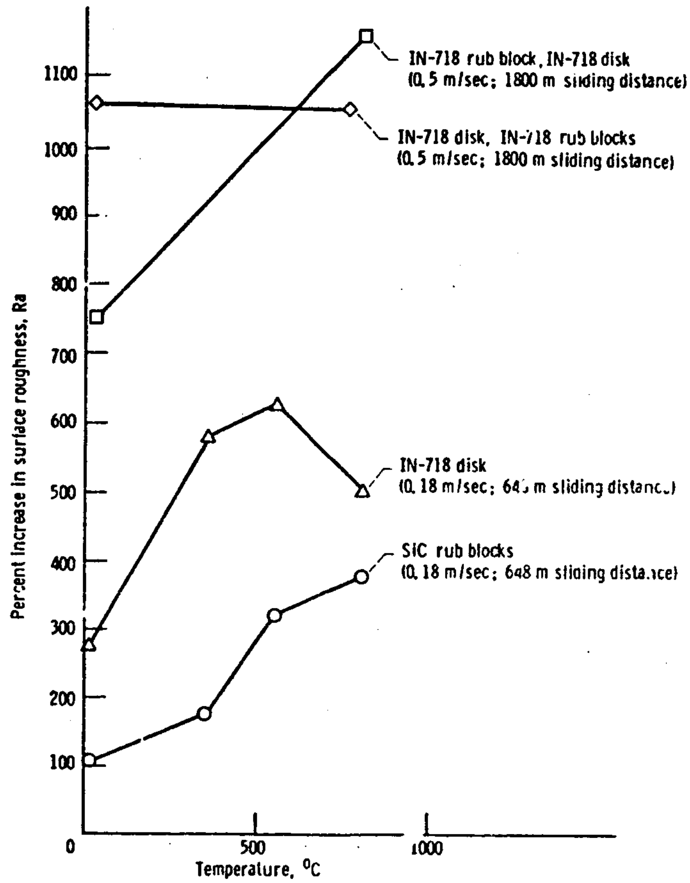
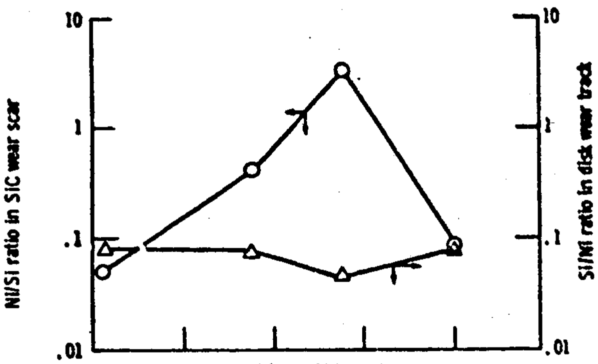
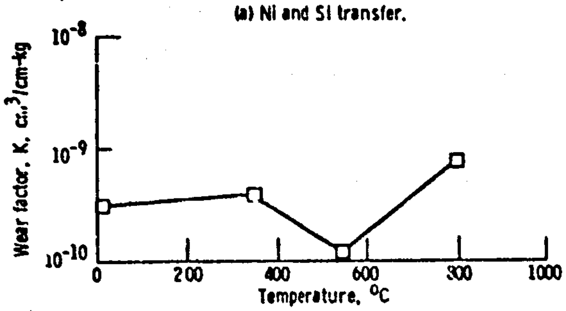


Figure 16. - Change in surface roughness (Ra) of SiC and IN-718 wear scars after sliding against IN-718 at 6.8 kg (67 N) load.



(a) Ni and Si transfer.



(b) Wear factors for SiC rub blocks.

Figure 17. - Wear factors and element transfer for SiC sliding against IN-718 in air from 25 to 800 °C (0.18 m/sec sliding velocity and 6.8 kg (67N) load).

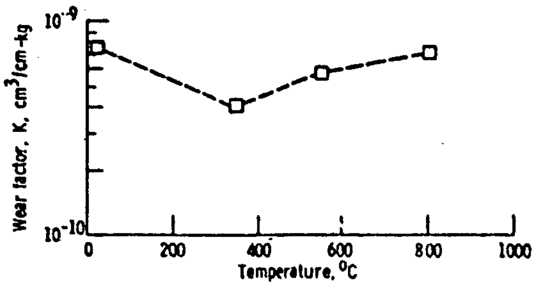


Figure 18. - Average wear factors, K (cm^3/cm-kg) for IN-718 disk sliding against SiC in air (45-55% RH), 0.18 m/sec and 6.8 kg (67 N) load versus temperature.

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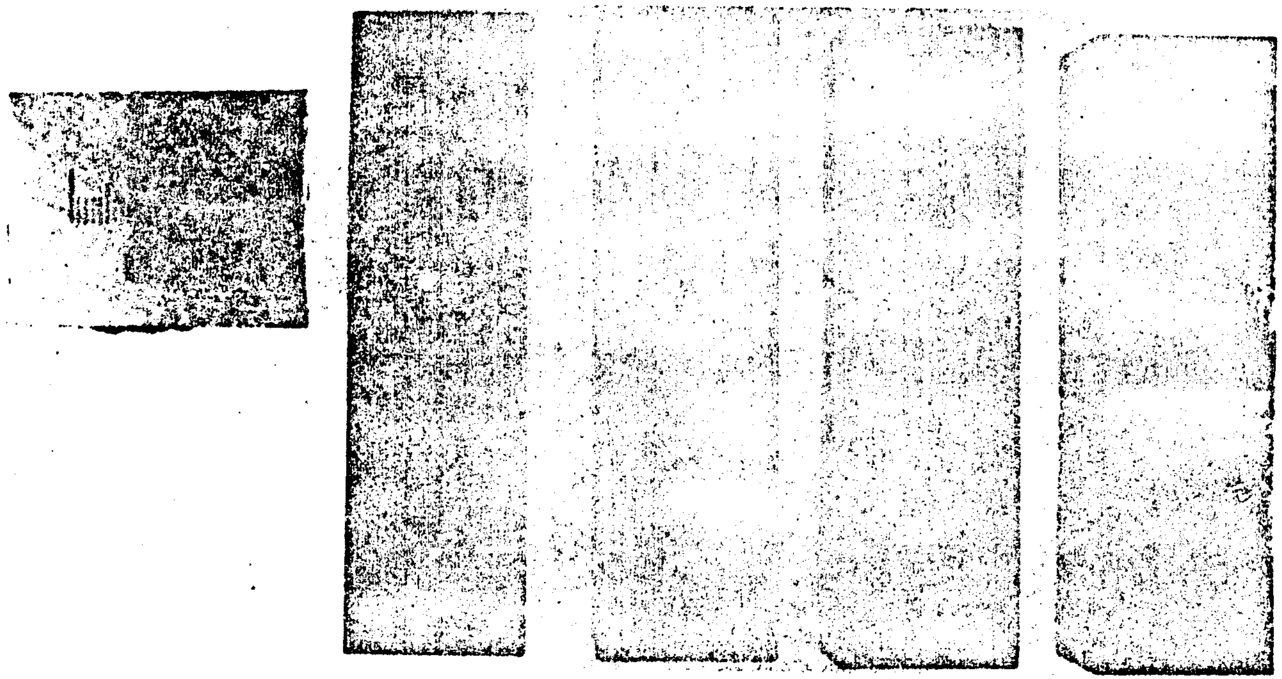

Figure 19. - Photograph of SIC rub blocks after sliding test. (550 and 800 °C blocks are gold coated for SEM examination.)

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15. Supplementary Notes

16. Abstract

The sliding friction and wear of the SiC-nickel based alloy IN-718 couple under line contact test conditions in atmospheric air at a linear velocity of 0.18 m/sec and a load of 6.8 kg (67 N) was investigated at temperatures of 25 to 800 °C. It was found that the coefficient of friction was 0.6 up to 350 °C then decreased to 0.3 at 500 and 800 °C. It is suggested that the sharp decrease in the friction in the range of 350 to 550 °C is due to the lubrication value of oxidation products. The wear rate reaches a minimum of 1×10^{-10} to 2×10^{-10} $cm^3/cm/kg$ at 400 to 600 °C.

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